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J85 REJUVENATION THROUGH TECHNOLOGY INSERTION

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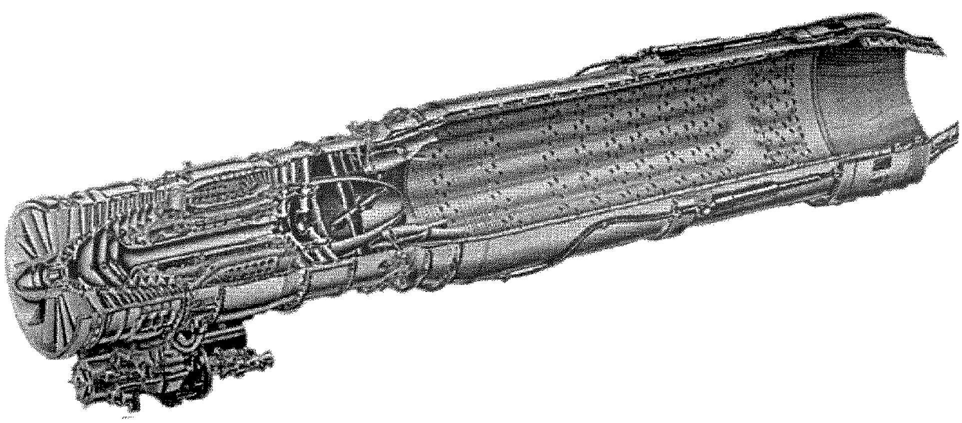

Summary

The history of the General Electric J85 turbojet engine is presented from its early inception as a single-use drone engine to its equipping of almost 3,000 frontline fighter and attack aircraft. The technology development to enable this progression and provide support of over 7,000 in-service engines is further discussed, allowing its continued use for the next 40 years. Specific examples of technology insertion are detailed, including a discussion of the innovative program leading to upgrade of the J85-powered T-38 fleet and options for the rest of the world's air forces.

Keywords

J85, CJ610, CF700, T-38, F-5, PMP, turbojet, compressor, spooled rotor, Inconel, ejector

Initial J85 Development

In the early 1950s, General Electric (GE) began design work on a series of very small, high thrust to weight ratio turbojet engines with potential application to early cruise missiles and drones. Initially using a compressor with only seven stages, a configuration using eight stages was finally settled on to provide for adequate performance margin, which proved to be prophetic. These design efforts resulted in the J85-GE-1 engine, and at 1,900-2,100 lbs. of dry thrust powered the GAM-72/ADM-20 Quail decoy missile (Figure 1) deployed on USAF B-52 bombers. Besides needing high thrust in a lightweight package, most other requirements were fairly benign. A reasonable airstart envelope was specified due to its being an air-launched missile, and a 30-minute, one-way mission life was all that was needed.

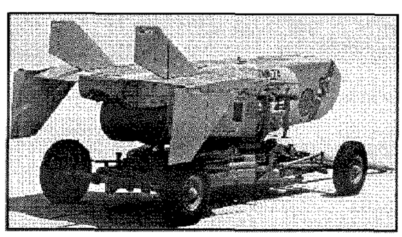

Figure 1: McDonnell Douglas ADM-20 (GAM-72) Quail

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The high thrust to weight ratio, small size, and good fuel economy brought the engine to the attention of aircraft designers at Northrop. These designers were in the process of digesting the lessons of the air war in Korea, where high speed, high ceiling, maneuverability, and long range were all at a premium. Northrop was also analyzing the results of a survey they conducted with users around the world, which drove Northrop towards development of a high-performance lightweight fighter (World Airpower Journal, Vol. 25, Summer 1996).

The J85 goes Manned and Reusable

By 1954, Northrop's aircraft studies in lightweight fighters and associated trainers centered on using the J85 (Scutts, 1986). Their N-156 series of designs utilized two of the engines in an afterburning configuration to achieve the necessary maximum speed and maneuvering capability. It was at this point that the humble beginnings of the J85 as a missile engine began to raise problems.

Selected by the USAF to build a supersonic jet trainer, Northrop's N-156T design became the YT-38 Talon. This selection was dependent on successful flight testing of prototype aircraft powered by J85 engines (Scutts). However, design work was necessary to increase the dry thrust of the engine, increase its service life, and adapt it to withstand the effects of the afterburner, not to mention a greatly expanded flight envelope. Pending the results of these efforts, however, the decision was made to install modified, non-afterburning J85-GE-1 engines in the first prototype T-38. April 10, 1959 marked the first flight of the J85 as the primary powerplant of a manned aircraft, successfully reaching 0.9M and a height of 35,000 feet, achieving supersonic flight in a shallow dive only a few days later (Scutts). The second prototype was also outfitted in this manner.

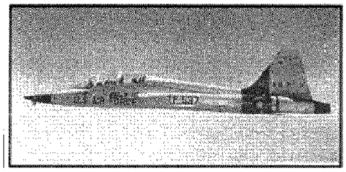

Figure 2: Northrop T-38A

Following successful development, the definitive afterburning version of the J85 for T-38 aircraft (Figure 2) was the J85-GE-5, which was installed on the first production aircraft and began flight testing in January 1960. The –5 produced 2,850 lbs. of thrust dry, and 3,850 lbs. of thrust in afterburner. In all, 1,187 T-38s were produced.

Closely following the development of the T-38 was Northrop's N-156F design, a single-seat fighter sharing many of the major components and characteristics of the T-38 and eventually becoming the F-5 (Figure 3). Being so close in timing to the T-38, the first F-5 prototype was also fitted with J85-GE-1s, going supersonic on its July 30, 1959 maiden flight even with these non-afterburning engines (Scutts). The production F-5A/B series of aircraft were equipped with the J85-GE–13, producing 4,080 lbs. in afterburner.

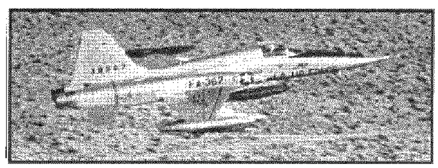

Figure 3: Northrop F-5A

The material used in the eight-stage compressor rotor and blades was steel-based AM355. These materials were consistent with the expected usage, environment, and anticipated service life of these original aircraft and other potential applications. The inherent versatility and flexibility of the J85 led to the development of multiple versions to be the primary powerplant for a substantial number of military aircraft, and as an auxiliary thrust powerplant for others (Figure 4). It even came full circle back to its beginnings, powering the Teledyne Ryan MQM-34 Mod II reusable drone.

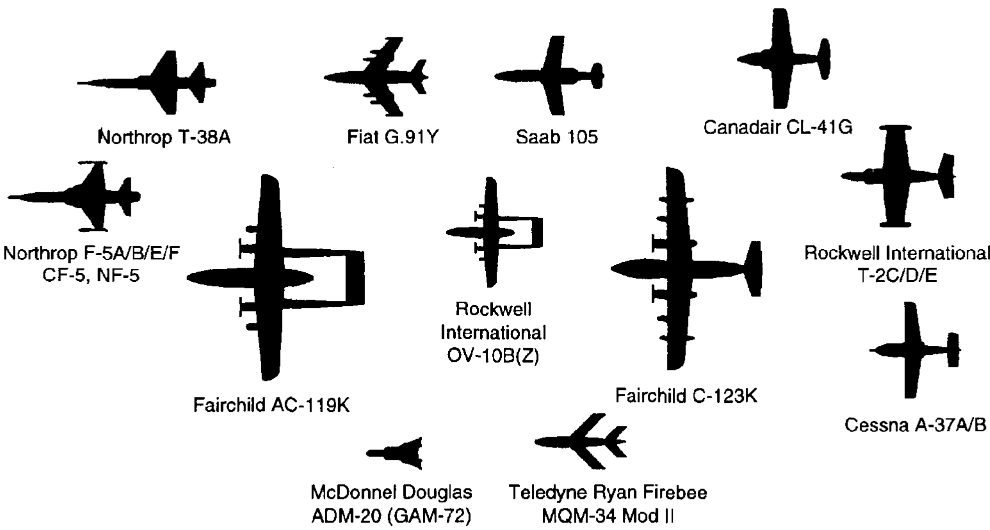

Figure 4: The J85 Aircraft Family

Being incorporated on this wide variety of aircraft ensured a long-lived, robust production volume. An impressive total of 9,592 engines were built, including licensed production, as shown in Table 1. At last count, some 4,500 of these engines were still in active service around the world, accumulating over 900,000 flight hours annually. In addition to military production, the J85 was developed into civil versions as well. The CJ610 and CF700 series of engines shared the compressor and basic configuration of the non-afterburning J85 versions, with the CF700 utilizing an aft fan for increased performance. Over 3,100 of these engines were produced and powered the early Learjet 24/25, Hansa, Westwind, Falcon 20, and Sabre 75 business jets.

Model	Number Produced	Aircraft Type(s)	Engine Type	Thrust (lbs)
J85-GE-4	740	T-2C/D/E; OV-10B(Z)	Dry	2,950
J85-GE-5	2,826	T-38	Afterburning	3,850
J85-GE-7	577	ADM-20, MQM-34	Dry	2,100
J85-GE-13	2,330	F-5A/B	Afterburning	4,080
J85-GE-13A*	201	G.91Y	Afterburning	4,080
J85-CAN-15*	609	CF-5, NF-5	Afterburning	4,300
J85-GE-17	544	AC-119K, C-123K	Dry	2,850
J85-GE-17A	1,404	A-37	Dry	2,850
J85-GE-17B	101	Saab 105	Dry	2,850
J85-CAN-40*	260	CL-41	Dry	2,850
Total	9,592			
* = Licensed Production				

Table 1: Eight-Stage Compressor J85 Engine Production

A New Nine-Stage Compressor for Increased Thrust

As with most fighter aircraft programs, Northrop began investigating ways of offering improved performance in its F-5 series to counter the growing capabilities of threat aircraft and countries. Predictably, these centered on increasing the thrust available from the current J85 series. GE had begun testing on a new nine-stage compressor of increased diameter in 1963 (Scutts), with the goal of creating a J85 that could produce over 3,800 lbs. of thrust dry and 5,000 lbs. of thrust in afterburner. The new compressor rotor and blades were made of titanium alloy, primarily to decrease the weight associated with the increased size. The rotor itself eliminated many of the individual disks that were used in the previous compressor by going to a spool concept, which essentially combined multiple disks into a single continuos part. These changes produced a compressor with a much greater pressure ratio and airflow, decreased parts count, and which also drastically reduced any susceptibility to corrosion compared to the previous AM355-based eight-stage compressor.

This version of the J85 became the J85-GE-21, and was flown on a modified F-5B on March 28, 1969. The –21 became the production engine for the F-5E/F aircraft, and flew for the first time on an F-5E (Figure 5) in August 1972 (Scutts). When production of this engine ceased in 1987, 3,482 units had been produced including 170 under license. Approximately 2,500 engines remain in service today.

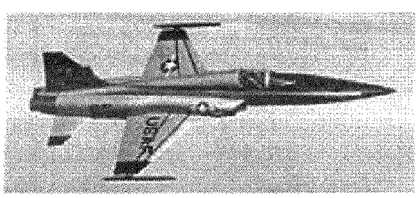

Figure 5: Northrop F-5E

Updating the Eight-Stage Compressor

In the 1990s, the USAF had approximately 500 T-38s powered by the J85-GE-5 still in service, with other users having active fleets as well. Various studies and analyses by the USAF on how best to accommodate their advanced flight training requirements led to the development of a comprehensive T-38 upgrade program. This program committed substantial resources to avionics and aircraft structural improvements significant enough to warrant an aircraft designation change (to T-38C), enabling T-38 operations until the 2040 timeframe, some eighty years after its first flight. However, limited effort was devoted to addressing propulsion system reliability and performance. It was against this backdrop that the 1995 loss of a T-38 due to engine failure led to efforts to address modernization of the propulsion system as well.

Through operational experience, it became known that the AM355 material properties and disk configurations of the eight-stage compressor were susceptible to corrosion over time, which led to pits and cracks affecting the calculated low-cycle fatigue limits. A series of life limit decreases were implemented over the ensuing years, driving increased maintenance costs of the J85 to ensure adequate safety. Exacerbating this susceptibility were changes in the mission environment and usage that were not fully documented. Understandably, subtleties in the usage and its effects on the design had crept in since the original rotor was developed in the late 1950s, not the least of which was a 50% increase in the mission severity factor for low-cycle fatigue. The management and premature retirement of the compressor rotors became the number one maintenance driver for the T-38 as a result.

Development of a spooled rotor, similar to the design of the nine-stage –21 titanium compressor, was proposed through the USAF Component Improvement Program (CIP) in 1994 to address the reduced compressor rotor life limits. The cost of this program exceeded available USAF funding at the time, and the life cycle cost analysis did not support giving the project very high priority. In 1995, operational events drove a re-examination of the need for a new rotor, with the most significant one being the loss of a T-38 due to engine failure. Investigation into this mishap revealed that an uncontained failure of an 8th stage compressor disk had occurred, with corrosion identified as the root cause. Clearly, a program to address the life of the compressor rotor was required if the T-38 were to remain operational as planned.

The USAF's boundary conditions for developing a new rotor system for the J85-GE-5 were quite severe, with overall cost and minimized

program risks being primary considerations. No major aircraft modifications were allowed, the new rotor design had to be a "drop-in" replacement to ensure maximum compatibility with in-service engine components, and a weight increase of no more than 10 lbs. per engine was specified. These conditions were made all the more difficult by the limited availability of CIP funding from the USAF to accomplish this task. With increased CIP funding being highly unlikely, the USAF asked GE to consider a team approach to launch a viable design and production effort.

GE responded positively to this request and proposed a team consisting of the USAF, GE, and ABB Alstom to share the development cost. Due to the exceptional number of in-service eight-stage compressor engines around the world, there was a viable business case for a new rotor design outside of USAF purchases. This situation allowed the creation of a unique investment, certification, and data rights agreement that minimized the USAF's CIP investment. Essentially, the agreement allowed the USAF to limit its investment to approximately 15% of the expected development cost upfront, essentially providing the seed money for the program. GE and ABB Alstom agreed to fund the remainder of the development and certification in exchange for exclusive rights to the eventual design. The design was to be certified to U.S. Federal Aviation Administration guidelines under FAR33 rules, with the proviso that GE and ABB Alstom provide additional information to the USAF under the CIP umbrella for analysis and verification. As a consequence, the new rotor would be made available in a commercial catalog, with standard commercial terms, conditions and pricing. The innovative approach sponsored by the USAF allowed the service to realize a huge return on a relatively small investment.

With the business side taken care of, attention turned to the task of designing a new rotor. Fundamentally, the airflow characteristics and aeromechanics of the current compressor design were exceptionally sound, and there was considerable reluctance to change the flowpath configuration in any new design. The decision was made to keep the current airfoil and flowpath contours, which would also allow use of the existing cases and stators with minimal risk. The primary need was to select a new rotor material that would eliminate the risk of corrosion, and marry it to the spooled rotor concept developed for the –21 engine.

At first, it appeared that use of titanium as in the –21 would simultaneously address the corrosion issue as well as minimize any weight growth due to rotor design changes. However, there was no previous GE experience of using steel-based blades in a titanium spool for the military environment. This combination had been successfully fielded in commercial engines, but the increased cycling and operational stresses inherent in military use raised concerns over fretting taking place at the blade to rotor interface. While there was the potential to provide a protective coating at this interface, it was felt that this introduced an unnecessary element of risk and would have increased long-term costs in maintaining the coating. Replacement of the AM355 steel blades with titanium blades was also considered, but was rejected due to the larger axial clearances needed and the incompatibility of the existing inventory of blades with the new rotor. The best solution appeared to be the selection of a steel-based material with corrosion properties superior to AM355, which proved to be Inconel 718.

Inco 718 had previously been used as a vane material in the J85, and promised excellent resistance to corrosion. With a target of a 3:1 increase in the low cycle fatigue life limit using both probabilistic and deterministic methodologies, a design was produced that replaced the eight individual disks with one disk and two spools (Figure 6). This redesign resulted in a dramatic 8:1 reduction in parts count, a 5:1 reduction in projected maintenance man-hours, and eliminated high stress concentration rim bolt holes. It also provides the capability for individual blade replacement without rotor disassembly or rebalancing.

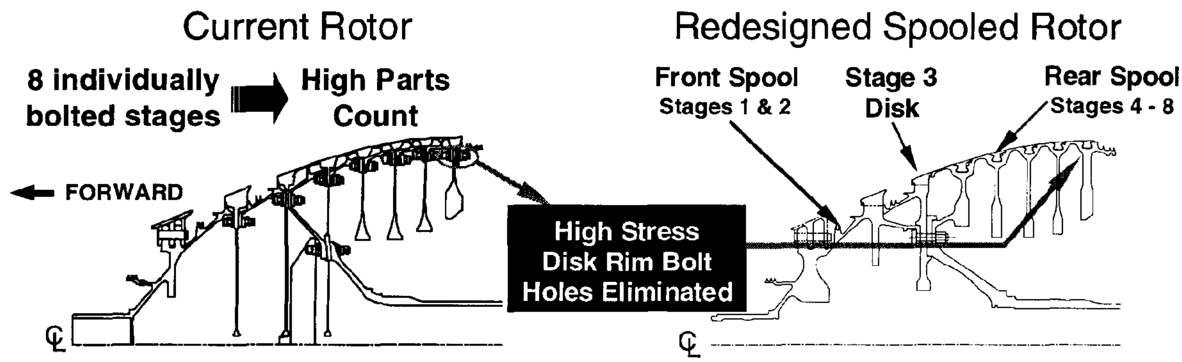

Figure 6: Design Comparison of Eight-Stage Compressor Rotors

However, by using Inco 718 versus titanium for the new spooled rotor design, the weight increased by 20 lbs. over the current rotor, exceeding the requirement by 10 lbs. The design was purposely conservative in order to be robust in service and have margin for the LCF life target, but could have been made somewhat lighter with further design effort. A study revealed the negligible impact of a 40 lb. propulsion system weight increase for the T-38, and the new design was accepted by waiver to the original and somewhat arbitrary weight requirement.

In keeping with the FAR33 certification process, the new compressor was not test flown on a military aircraft. Instead, the test vehicle was a Learjet 24/25 with one of its engines having been modified with the new compressor. The civil CJ610-6 engine is closest in configuration to the J85-GE-5, and a –6 was modified and flown to provide the necessary data for certification. This testing was completed in early 2000, with a dirty and clean layout inspection of the hardware scheduled for later that year. In keeping with the risk mitigation process employed throughout the redesign effort, testing of the new compressor was accomplished both with new compressor cases and older production cases representative of those that would be encountered during the retrofit program. All of these test combinations have been successful, with a spooled rotor expected to be available as a standalone, drop-in replacement kit (Figure 7) in late 2000.

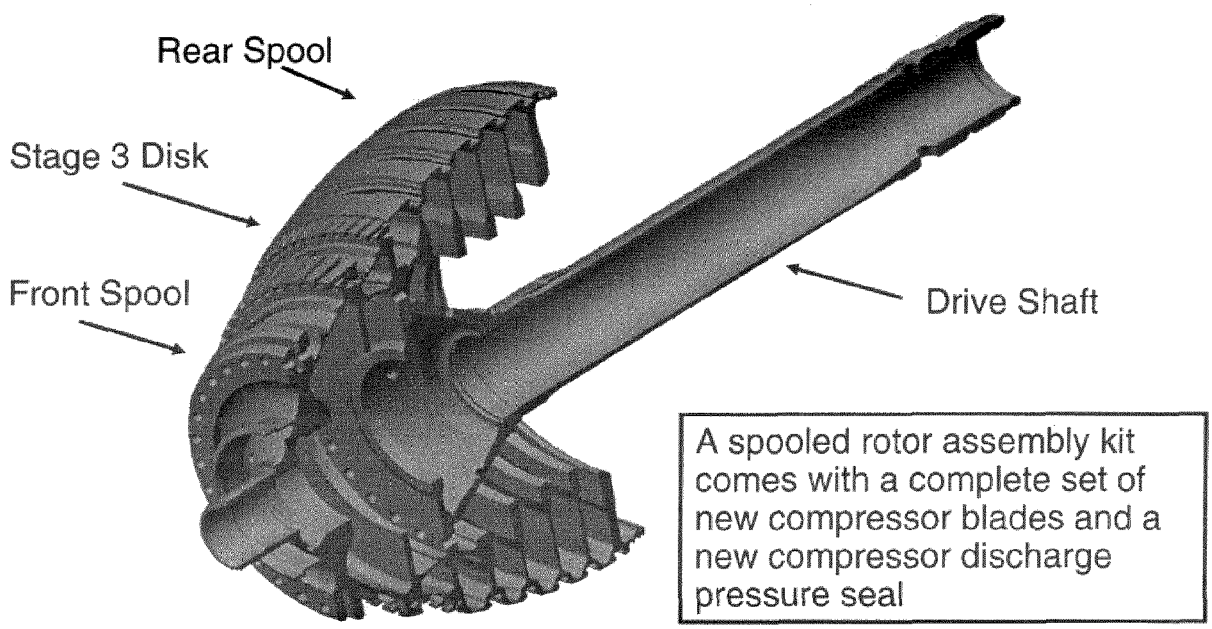

Figure 7: Redesigned Eight-Stage Compressor Rotor Assembly

Improvements Beyond the Compressor Rotor

The success of the initial look at updating the compressor rotor prompted the USAF to undertake a comprehensive review of what could be done to address other issues on the J85. This review centered developing a long-range propulsion roadmap that would be consistent with the T-38 structural and avionics upgrade programs allowing operations into the 2040 timeframe. The roadmap was to develop options that focused on reducing the cost of ownership, and increasing the overall safety, reliability, and durability of the propulsion system. These options fell into the broad categories of component improvements, engine module upgrades, aircraft system enhancements, maintenance-related changes, and even the possibility of re-engining. Table 2 lists some of the items analyzed during the propulsion roadmap study.

As with the spooled rotor redesign effort, funding to develop and acquire these upgrades was in short supply. Each task was analyzed for return on investment and life cycle cost benefit, and then balanced against the available funding. The net result of this study was the definition of a set of upgrades for the T-38C that would collectively be known as the J85 Propulsion Modernization Program, or PMP. At the heart of this upgrade program was the new eight-stage spooled compressor rotor described previously. Figure 8 identifies the major kits that comprise the PMP. While some of the upgrade items in Table 2 were not selected for the PMP, they remain viable candidate programs to address other customers' requirements for J85 improvements, while several more programs exist for the –21 version of the J85.

Components	**Modules**
Long Life Combustor	Spooled Compressor Rotor
Cast Nozzle Flaps & Seals	Mini-Growth Turbine
Stacked-Ring Afterburner Liner	New Design Turbine
Ignition Plugs & Leads	New Turbomachinery
Variable Geometry Actuator	New Design Compressor
Compressor Case	
Ignition Exciter	**Aircraft Systems**
Afterburner Fuel Pump Upgrade	Ejector Nozzle
Main Fuel Pump Upgrade	Inlet Lip Modification
Hydraulic Nozzle Actuation	
Afterburner Fuel Control	**Maintenance**
Digital T5 Amplifier	T5 Motor Overhaul
Mainframe Upgrade	Overspeed Governor Overhaul
Full Authority Digital Engine Control	Master Chip Detector
T2 Sensor Replacement	Heatshield Access Port to Igniter
Compressor Bleed Valves	
	Re-engining
	New Centerline Engine
	Alternate Engine

Table 2: T-38/J85 Propulsion Roadmap Items

The PMP wasn't just a program to put old part designs back into production, making new "old" production hardware. The opportunity to analyze significant amounts of field data and apply state of the art materials, designs, and production techniques was taken with a vengeance.

In conjunction with providing a new compressor rotor, new stator cases were made available with increased corrosion resistance. This was accomplished by changing from AM355 base material with coating in the stator lands to Inconel as the base material, eliminating the need for coatings and their high-maintenance care.

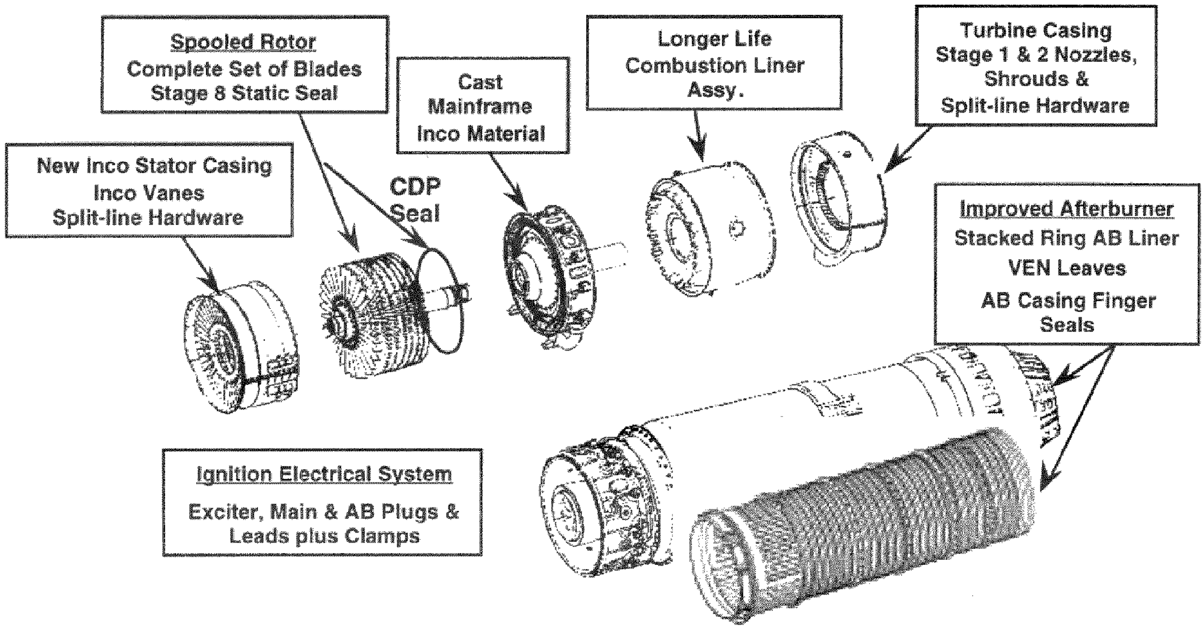

Figure 8: J85 Propulsion Modernization Program Upgrades

A new single-piece cast mainframe was created to replace the original 39 piece welded design, as well as introducing Inconel for improved corrosion resistance. The welded design was susceptible to fatigue cracking that originated along the edges of the welds joining the struts and pads to the outer shell. While repair of the cracks is possible, it is expensive both in cost and engine down time.

Taking advantage of new materials and coatings allowed a significant increase in the reliability of the J85 combustor. By applying revised thermal barrier coatings (TBC) and placing it in additional areas of the combustor, both the service life and inspection intervals have been increased by a factor of 2 to 1.

Addressing the traditional high distress area of engines was accomplished by providing a comprehensive upgrade kit for the high pressure turbine section. A new turbine casing with revised Stage 1 and 2 nozzles was able to reduce cracking by porting cooling air to new areas. New shroud and turbine blade materials increased the temperature capability, allowing greater time on wing.

Decreasing the maintenance costs and increasing the reliability of the afterburner was a major focus of the PMP, as liner cracking was the leading cause of unscheduled engine removals. The current liner design consists of 4 major sections and containing over 900 parts in total. The brackets used to support the liner produced high stress concentrations. A new stacked ring liner was designed that is a single major piece, with less than 100 additional parts required to complete the assembly. The bracket system was eliminated entirely by transitioning to a free-floating design, and TBC was applied in the screech section. Durability for the liner alone was increased by a factor of 6 to 1. New variable exhaust nozzle (VEN) leaves and afterburner casing seals, changed as a set, have revised chrome carbide and electroless nickel coatings for a 3X service life improvement.

Perhaps more mundane but no less critical, the issue of electrical parts obsolescence was tackled in the engine ignition system. Certain ignition exciter components are no longer available at any price, and the overall design was seriously outdated (1950's electronics technology). By utilizing a modern exciter with new plugs and leads, overall ignition energy and system reliability is dramatically increased, resulting in a reduction of no-starts and afterburner no-lights by over 50%.

System Level Improvements

The J85 engine is but one component of the T-38 aircraft propulsion system, and the entire system was evaluated in developing technology options for improved performance and reduced cost of ownership. Two items identified in the propulsion roadmap fall into this category of improvement, the ejector nozzle and the inlet lip modification.

The original configuration of the T-38 nozzle ejector was sized for the maximum afterburner condition. This exit area caused over-expansion of the exhaust plume at Military power, with the result being excess drag and lower overall net thrust. A new system was designed that incorporated free floating doors in an ejector that was a simple replacement of the current hardware. The aerodynamic actuation system resulted in an effective variable size at all power conditions, more efficiently controlling the plume expansion. This provides a system level benefit in terms of higher net thrust of 1-2% at takeoff conditions and up to 10% at Military power, resulting in decreased fuel burn or increased aircraft performance. In addition, the stall-free engine envelope was increased, and the nozzle components were exposed to a decreased temperature environment. Figure 9 shows the basic configuration of the revised ejector design, and Figure 10 compares the installation of the revised design to the current.

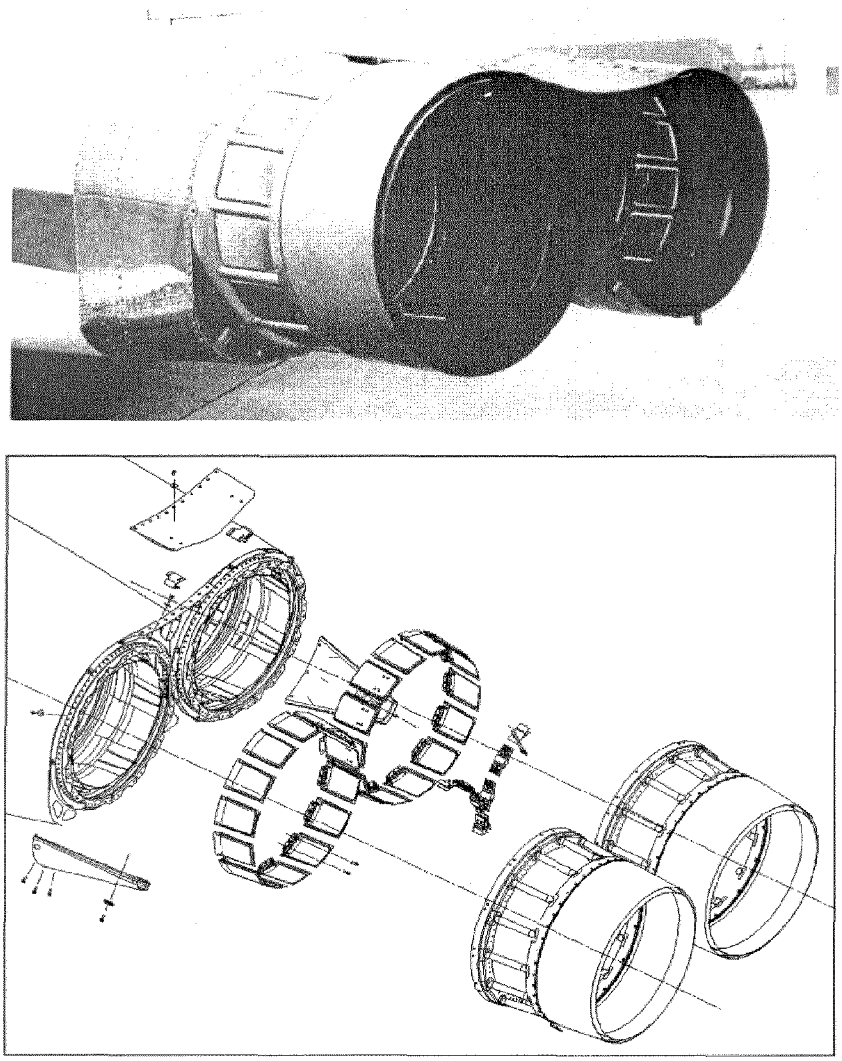

Figure 9: Redesigned Ejector Hardware

The redesigned ejector nozzle is shown installed on a NASA T-38, which accomplished a series of risk-reduction flight tests to validate the projected performance characteristics and improvements. The results of the flight test are shown in Figure 11 plotted on an aircraft flight map with areas of anticipated performance increases displayed, confirming the analytical model of the ejector.

This significant performance increase could be even further enhanced with the incorporation of a revised inlet lip contour. The T-38 was the first aircraft to go into production in Northrop N-156 family, and subsequently aircraft models used modified inlet configurations to improve engine performance and stall margin. Using this design history as a base, a new inlet shape incorporating a fatter lip with a squarer profile was developed. This new design was also tested on a NASA T-38 in the form of an add-on glove to simulate replacement of the current design, resulting in a startling 22% thrust increase at take-off conditions, with improved stall margin throughout the envelope.

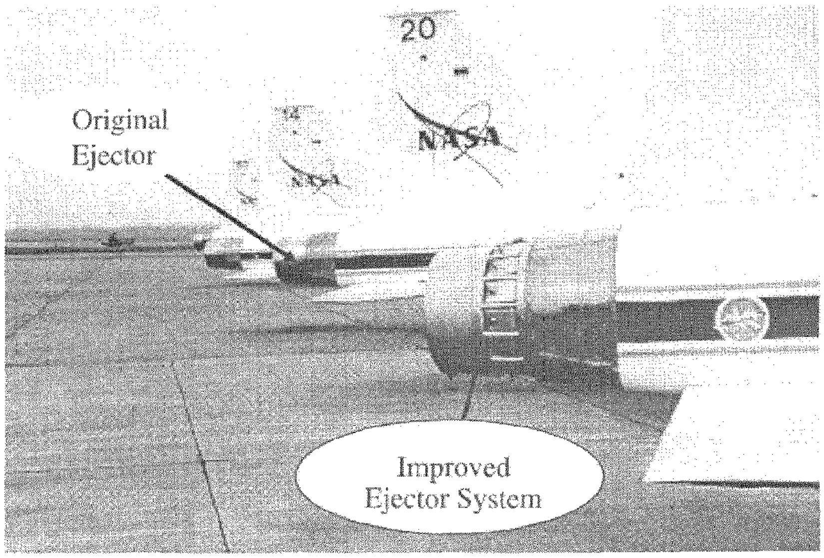

Figure 10: Comparison of Original Ejector to Improved Ejector System

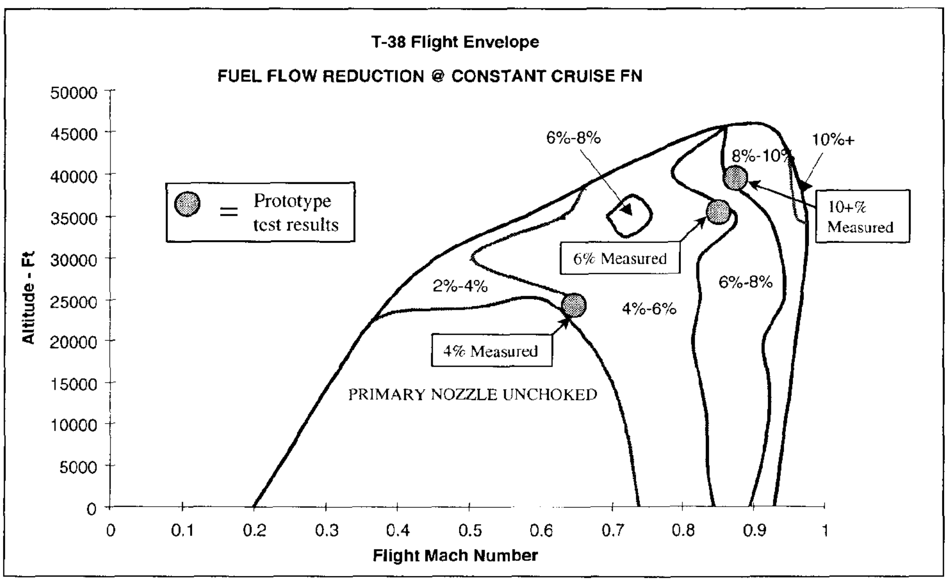

Figure 11: Ejector Nozzle Flight Test Results

Summary

The technologies and design capabilities available for new engines today were only a gleam in propulsion engineers' eyes 50 years ago. The performance, operating costs, inspection intervals, and service life of engines designed in that timeframe pale in comparison to modern military engines. But those modern tools, combined with a rigorous and honest analysis of fielded engine experience, can produce technology upgrade options that rejuvenate engine performance and reliability, yet are affordable to acquire.

The J85 engine is a classic example of an engine with very modest beginnings being called upon to serve longer and used much more differently than was ever originally imagined. With acquisition of new aircraft all but impossible due to continually decreasing military budgets, soldiering on with existing equipment is the order of the day. A committed manufacturer, seeing with the eyes his customer, cannot help but to support the continued operation of aging engines with the technological and intellectual resources at their disposal. Indeed, GE Aircraft Engines has embodied this spirit of commitment in its internal policies, stating "GE Aircraft Engines (GEAE) will continue to provide support for all GEAE products for as long as any operator continues to use the products." By rationally packaging kits of engine upgrades that increase time on wing, scheduled inspection intervals, and overall system performance, it becomes possible for users to break the death spiral of increasing maintenance costs.

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